Understanding track loading requirements to achieve better track design

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Abstract

This paper reviews current track loading requirement (ballasted and ballastless) Typical vehicle-track interaction loads are described along with their influential factors. Limits and influential factors are analysed against statistical evidence from vehicle dynamics measurement. Additional load combinations are presented as potentially relevant for track design. Discussion are made on the potential reduction of load from improved vehicle performance and slab track improved geometry, areas which might bear some benefits in terms of cost reduction for future slab track designs. This paper demonstrates that both vehicle measurement and simulations can provide an important source of information in terms of expected track loading and their limit values to help achieve cost reduction in track design.

Keywords: Vehicle-track interaction, vehicle dynamics, track forces, track design, ballast, ballastless.

1 Introduction

Since the volume and speed of the railway freight and passenger traffic is expected to increase in the near future, infrastructure managers are given more and more opportunities to turn towards ballastless technology to help their infrastructure achieve the required long term reliability, availability, maintainability and safety while reduce life-cycle costs. However insufficient knowledge exists about the long term behaviour of ballastless track, with the exception of specific targeted applications in Germany and some return on experience from Japan and soon China. To make matters worse, the numbers of slab track systems available are wide ranging with various designed options being promoted by independent private enterprise while the industry as a whole often lacks precise guidelines and methods to allow robust designs to clearly emerge and new solutions to be fairly assessed. An

objective assessment methodology to inform on which type of application makes ballastless track a more economical option than ballast is not currently available. The mechanical loading for both ballasted and ballastless track is key to this assessment but is too often misunderstood. The track loadings have inherent variability both in spatial and frequency domain which are a function of a wide range of parameters belonging to both sides of the interface between vehicle and track, for example the track layout and the vehicle operating conditions. The impact that support condition has on the ability of railway track to retain its geometry and minimise track load variability is not currently monitored and not sufficiently addressed in the design process.
This paper summarises the current approach to track loading considerations with respect to design as addressed in the current Euro norms. It then describes the role and key functionality of the track superstructure as a loading interface between vehicle and supporting structures (subgrade, embankment etc…). Track loading are then described on the basis of their variability with space and frequency, focusing on vertical and lateral loadings only (traction and braking are out of scope). The core of the analysis work in this paper is based on statistical analysis of vehicle measurement and vehicle dynamics based output to judge on the level and frequency of loading with respect to the current limits in the Euro norms. Finally discrepancies areas are highlighted and areas of further work discussed.

1.1 Current standards and guidelines on track loading

A draft European standard prEN16432-1:2012 [1] on ballastless track systems general requirement including load requirement has been issued, which largely refers to current loading requirements for bridge structures EN1991, making use of the Load Model 71 while combining best practices from track load requirements emerging from vehicle acceptance procedures under EN14363:2013 [2] and UIC518 [3] leaflet. An interesting development is that the standard suggests that in the case of dedicated fleets (100% HS lines for example), more advanced vehicle-track interaction modelling can be used to justify the expected loads the track will experience, and therefore help achieve a streamed down economical design which would otherwise not be achievable if LM71 model is used for example.

1.1.1 Vehicle related standards and limit values

Both standards related to vehicle acceptance and testing [2] and [3] specifically aim at limiting loading on track to prevent: track shifting or buckling, component damage and general geometry deterioration. Note that in vehicle testing all measured forces are low pass filtered below 20Hz and therefore dynamics forces are mainly associated with corresponding vehicle dynamics effects and response to track geometry features of wavelength in the range 1m to 70m or up to 150m for high speed. Higher frequency response associated with discrete track defects events which have an impact on track structure are addressed separately. Quasi-static loads (Qqst and Yqst) are separated from dynamics load components (Qmax and $\sum Ymax$) in signal processing and limits compared accordingly.

1.1.2 Structure related standard and limit values

Current TSIs specify track resistance on applied vertical, longitudinal and lateral loads for conventional rail (CR) [4] and high speed (HS) infrastructures [5].

For vertical load, three components are considered: maximum static axle load, maximum dynamics wheel load and maximum quasi-static wheel force.

Furthermore on structures reference is made to LM71 of EN1991-2:2003 multiplied by a factor (α) equal or greater than 1. Dynamic factor (Φ) is also referring back to En1991-2:2011 section 6.4.3 and 6.4.5.2 which essentially consider the vibration effect of a bridge structure (its characteristic length) in combination with track quality and maintenance level. This definition is not entirely adequate to the case of non-bridged structures. Two main types of slab track systems may be expected to have different vibrational behaviour depending on whether they are continuous (e.g. continuously cast concrete) or prefabricated fixed length slabs. Furthermore the way the slab system interacts with the supporting foundation and its given modulus will determine its vibration characteristics.

For lateral loads the TSI specify that the track should resist the maximum lateral forces exerted by an axle on the track. The HS version specify that this maximum forces is due to acceleration non-compensated by track cant referring to the Prud'Homme limit of equation (1) with P = static axle load in kN, although originally this limit was obtained through testing for track buckling under unstable vehicle on 50kg rail track with wooden sleepers. Arguably this result would be highly different on modern ballasted track and even more so on slab track. The conservative nature of this limit is discussed later on in the paper. The track should be able to withstand quasi-static lateral guiding force Yqst in curves and switches and crossings (S&C). Note that S&C are out of the scope for this paper.

$$(\Sigma Y_{2m})_{lim} = 10 + \frac{P}{3}\ [kN] \tag{1}$$

Regarding structures two lateral forces components are mentioned: centrifugal forces in curves section 6.5.1 of [6] which depends on vehicle speed and curve radius; secondly the nosing force section 6.5.2 of [6] which depends on the potential instability of running vehicles applied in both straight and curved track. A limit force of 100kN is envisaged, to be combined with vertical loads during the assessment and it is specified that this force is applied on both rails but no proportion is given so it is assumed that the full 100kN correspond to the total track shifting forces to be achieved.

1.2 The role of the track system in terms of load

Track systems are required to support and guide trains while resisting their load and protecting their supporting infrastructure, so that no or very little subsidence occurs over long time periods. This is achieved by effectively spreading the loads from the wheel rail contact (highest stress concentration) to the sub-grade (lowest stress concentration), in order to minimise permanent deformation over time and reduce the risk of failure [7]. The rail shape includes radiuses on the crown and is inclined so as to match the conical shape of the wheel and offer an area of contact typically of the size of a thumbnail. Depending on the worn shapes, dynamics effects and nominal payloads, the resulting stresses within the rail can often be beyond the yield strength and therefore material deformation occurs so is wear and fatigue. The second function of the rail is to offer vertical and lateral strength acting as a beam in both these directions to as to spread the load over a number of sleepers. For ballasted track this is typically of the order of three to four sleepers, with up to 50 to 60% of the nominal wheel load acting through one sleeper. Depending on the resilience or stiffness of the rail fastening and pad assembly, as well as the ballast support stiffness, the deflection of both these elements will also govern the way the overall system reacts and the way the load is distributed. For example soft rail pads will help distribute the load over more sleepers and therefore reduce the peak force on any one sleeper or fastening. Current trend in increasing rail section bending properties (EI) helps distribute the load more evenly over more sleepers, to protect the track components and also reduce ballast stresses.

In case of slab track, the sleepers disappear to make place for a continuous reinforced concrete beam or slab, either continuously formed or with pre-cast fixed length sections. This means that the slab will generally act as a far more rigid system in comparison with individual sleepers able to move up and down independently over the ballast layer. This means that the fastening and pad system are taking the main role of letting the rail deflect to distribute the forces over sufficient distance. Generally slab track system use lower resilient fastenings, the lowest example probably being the Vanguard stiffness as low as 4kN/mm (other low resilient fastening are in the order of 20 to 30kN/mm).

In all cases, ballasted or non-ballasted track, it is important to design and choose the right properties (bending and stiffness) so that the overall system allows an optimum share of the stresses across the system, along its length and from top to bottom across the different level of resilience. This implies a good understanding on the one hand of the impose vehicle loads, as well as the resilient stiffness of the supporting layers (geo-civil).

2 Vehicle-track interaction loads

The wheel-rail interface is the key area of exchange of loads between vehicles and railway track. Therefore loading on a railway structure occurs as a series of moving concentrated load points, depending on the train's configuration (section 2.1) and moving speed (section 2.2). The vertical and lateral concentrated loads on the rail head can vary highly. First it might be easier to characterise them by separating the quasi-static loads (section 2.2) from their dynamic counterpart (section 2.4), which is adding extra force fluctuation but over shorter distances or duration (function of the moving speed). The dynamic force component can therefore further split into low frequency and medium frequency and high frequency ones (section 2.4).

2.1 Vehicle type and configuration

2.1.1 Axle load

The type of vehicle clearly influences the loading, with at the low end empty freight wagon and empty passenger rolling stocks (low axle loads starting at about 5t per axle). Then come heavier passenger high speed trains and crushed laden multiple units (ranging between 11t to 17t axle load). Finally locomotives and laden freight wagons which come close to the permissible axle load of 22.5 or 25 tonnes per axle. Note that heavy haul applications such as for Iron Ore in Sweden, Australia or south Africa are exploiting 30t axle loads and looking at increase up to 35t and 40t.

2.1.2 Axle spacing

The proximity of loads also impacts on the load distribution over track distance and the way two consecutive loads might interact and add to local track deflection. This depends on the vehicle configuration, that is number of axles (example 2 axle freight wagons or bogied freight wagons), the spacing between bogie centres in a vehice, the wheelbase and number of axle per bogies (usually two but often three for heavy haul locomotives). Freight vehicle might have bogie wheel base as short as 1.8m while high speed passenger coaches have much longer bogies of the order of 3m between axles. Generally the bogie spacing on a vehicle is wide enough to avoid an interaction of loading pattern on the track, however, two bogies either ends of two attached vehicles might both contribute to the load and deflection exerted on the track.

2.1.3 Suspension and wheel conicity

The type of suspension of a vehicle greatly influences the dynamic performance and therefore dynamic loads onto tracks. Generally speaking passenger vehicle with their relatively low axle loads and their sophisticated suspension elements (e.g. airspring secondary) will generate relatively smooth and low magnitude variation in loads. On the other hand freight vehicles are low cost built solutions, making use in large part of dry friction damping elements, which can introduce large and chaotic dynamic behaviour. Link to this is the fact that wheel maintenance and control is generally much lower on freight rolling stock, so that shape and equivalent conicity might degenerate far more than passenger rolling stock, thus adding to poor quality ride (stability) and curving performances. The other types of vehicle most relevant in terms of track loading are the locomotives because of their high axle load and their relatively unsophisticated suspension and running gear designs. In particular non-radial steering three axle bogies are very poor in steering through tight curves.

It can be foreseen that locomotive and heavy freight wagon are the principal vehicle of interest in terms of track loading characterisation.

2.1.4 Unsprung mass

Finally axle unsprung mass is also indirectly responsible for the generation of certain dynamic loads on track. Heavy unsprung mass including additional equipment like disk brakes and part of the traction motor and gear systems mass, tend to heavily react to short wavelength track disturbances and discrete defects. A typical example is where the mass is required to rapidly change direction working against its own inertia and reacting against track mass and stiffness at a dipped joint.

2.2 Track layout and operating conditions

The track layout, principally the curve radius forces the vehicle to passively steer around curves which occurs naturally through the conical shape of wheel and the rigid link made between the left and right wheels through the axle. Equivalent conicity of a pair of wheels on a set of rails is variable, changing with the worn shape of both wheel and rails. The higher the conicity the easier it is for an axle to steer around a curve with minimal lateral offset and angle of attack, and therefore minimal longitudinal and lateral creep forces respectively. The second factor of influence is the primary suspension stiffness in yaw, which if too stiff leads to high angle of attack because it resist the natural trend for the axle to steer around the curve by compressing the suspension. This is typical of freight wagon suspension which can be highly rigid and therefore leading to high lateral forces onto the rails in tight curves.

Cant deficiency is a factor of the vehicle speed, the track radius and the track cant elevation. For a vehicle to go around a curve at higher speed than the equilibrium cant allows, means the vehicle experiences non-compensated lateral acceleration or cant deficiency. This is often desired for passenger comfort, within specified limits (110mm or 150mm exceptional for example in the UK [8]), but necessarily generate weight transfer onto the high rail while generating net lateral curving forces onto the track. One benefit of cant deficiency on terms of track loading is that it generally helps rebalance the steering forces across a bogie, so that the difference in lateral forces between leading and trailing axles become closer. Otherwise the tendency is the leading axle to generate high lateral load on the high rails, while the trailing axle can generate track shifting forces in the opposite direction. Reciprocally to cant deficiency, a freight trains operating along a canted track at slow speed experiences cant excess, whereby the low rail sees increased vertical force.

2.3 Quasi-static loads

Quasi-static loads are equilibrium forces observed in steady state conditions, either straight track or curved track at steady speed. On straight track with no cant quasi-static forces equal wheel payload. However once curving, and cant deficiency or excess is introduced, there will be a rebalancing of vertical forces (Qqst) between the high and low rails. Wind lateral gust are also generally considered in weight

imbalance calculations. In the lateral direction, all the factors described previously influence the resulting quasi static lateral forces at any wheel (Yqst).
The lateral forces currently monitored according to standard are both the lateral force Yqst at any wheel (usually the leading wheelset on the high rail shows the highest values) and the $\sum Ymax$ which is the total force exerted by any axle onto the track. Note however that there are other combination of lateral forces which can be significant both in terms of understanding track degradation and track design. These are explained in section **Error! Reference source not found.**.

2.4 A classification of dynamic loads

2.4.1 Low frequency (below 20Hz)

Low frequency force variation is governed by the dynamic behaviour of the vehicle (mass, inertia, suspension characteristics) reacting to track geometrical irregularities (vertical, lateral, cross level and gauge) and overall changes in design layout (transitions between straight and curved track sections) as well as while changing track in turnouts. Track irregularities are measurement in the wavelength domain categorised in three bands: 3m to 25m (D1), 25m to 70m (D2) and 70m to 150/200m (D3) according to [9]. Irregularities above 70m are relevant for high speed vehicles and only analysed for high speed track. Irregularities below 3m do influence vehicle reaction however they are filtered out from vehicle recording data and can be considered to approach the medium frequencies forces (section 2.4.2). Standard deviation of irregularities in band D1 is generally used to quantify track quality in track sections of 100 or 200m. Track forces tend to proportionally increase as track quality deteriorates.

Quantities of interested in relation to low frequency forces are:

- Maximum vertical wheel force $Qmax_{<20Hz}$
- Maximum lateral wheel force $Ymax_{<20Hz}$
- Maximum axle lateral force $\sum Ymax_{2m}$ filtered with 2m sliding to reflect potential for sustained track shifting force

Track system design should ensure compliance with low frequency forces.

2.4.2 Medium frequency (in the range 20 to 90Hz)

$Qdyn_{<90Hz}$ and $Ydyn_{<90Hz}$ forces are generated from discrete events such as dip joints, weld repairs, wheel and rail surface defects (e.g. wheel flat or out of roundness) and load transfer at switches and crossings. They mostly generates an additional force component which amplitude and wavelength depends on the track stiffness and damping characteristics, the vehicle unsprung mass and its speed as well as the shape of the wheel or rail non-linearity. At this frequency the force is traditionally referred to as P2 force in the vertical direction and regional specifications exist for defining limit values for example Great Britain group standard GM/TT0088 [10]. It is transmitted to the supporting ballast and subgrade layers and lead to settlement as well as fatigue issues with rails, bearers, and cast crossings.

Control of this force must be done through better design of wheel-rail interface at S&C, better control of welded rail geometry as well as wheel and rail defects. However track superstructure design should ensure that medium frequency forces can be absorbed and dissipated effectively in order to help reduced impact and damage of the supporting structure.

2.4.3 High frequency (above 90Hz)

They are the higher frequency component of the above force, which includes the additional response from the wheel-rail mass coupling on the contact stiffness, traditionally called the P1 force. Current standards are not considering this force due to its highly transient nature (a few milliseconds), although it may arguably contribute to the generation of local rail and wheel material surface and sub-surface defects due to the very high magnitudes and the potential effect on material stresses.

Control of this force must also be done through better design of wheel-rail interface at S&C, better control of welded rail geometry as well as wheel and rail defects. However track system design at rail and fastening level should ensure that high frequency forces can be absorbed and dissipated effectively in order to help reduced impact and damage in the wheel-rail materials.

3 Analysis of track loading based on measurements

In order to support investigation into track loading characteristics and influencing factors, the data measured on EU project DynoTrain [11] was used, which offered a concurrent measure of both track characteristics (layout features and irregularities) and vehicle reaction (contact forces measured through instrumented wheelset). The data was processed in order to isolate relevant combinations of loads and contributory factors from track characteristics to vehicle operating conditions.

3.1 Introduction to the measurement data

Measurement was made in four different countries covering four track categories (slow speed to high speed) and covering all aspects of vehicle behaviour for a locomotive, a passenger coach and a laden and empty freight Y-series bogied wagon. Due to the large amount of data available, it was decided to narrow down and focus the analysis on one country (Germany) only and two vehicle types (locomotive and loaded 4-axle freight wagon) most relevant for high track loading as explained in earlier sections. The total length processed is, thus, 841.4 km divided in 19 runs. All track data has been processed according to [9] and vehicle measurement forces according to [2], with the exception that non steady state conditions have been included to the analysis, for example when the vehicle is in a transition curve and additional dynamic behaviour may occur (these are normally filtered out of vehicle testing). The input and output data are given in Table 1.

Table 1: Input data and output data of the statistical analysis

	Track parameters	Vehicle parameters
Input data	• Curvature **Curv** • Cross Level **CL** • Alignment **y** • Longitudinal level **z** • Permissible speed **Sp**	• Lateral force **Y_w1l, Y_w1r, Y_w2l, Y_w2r** • Vertical force **Q_w1l, Q_w1r, Q_w2l, Q_w2r** • Vehicle speed **V**
Output data	• Curvature **Curv** (mean value, SD) • Cant Deficiency **CantDef** (mean value, SD) • Alignment **y** (mean value, SD) • Longitudinal level **z** (mean value, SD)	• Lateral force **Y** (mean value, 0.15 percentile, 99.85 percentile) • Vertical force **Q** (mean value, 99.85 percentile) • Track Shifting $\boldsymbol{\Sigma Y_{2m}}$ (mean value, 0.15 percentile, 99.85 percentile) • Gauge spreading $\boldsymbol{Y_{gs}}$ (mean value, 0.15 percentile, 99.85 percentile) • Bogie skewing $\boldsymbol{Y_{bs}}$ (mean value, 0.15 percentile, 99.85 percentile) • Bogie total $\boldsymbol{Y_{bt}}$ (mean value, 0.15 percentile, 99.85 percentile) • Rail twist $\boldsymbol{Y_{rt}}$ (mean value, 0.15 percentile, 99.85 percentile)

3.2 Vertical loads

3.2.1 Influence of curve radius

Measurement are here compared to the limits suggested proposed in [1] in terms of quasi-static load factor (max(Qqst)-Q0)/Q0<+/-25% and dynamic load factor of (max(Qdyn-Q0))/Q0<+50%. This is shown as a green dotted line in Figure 1 and Figure 2 respectively, both plotted against curve radius.

Observations for the quasi-static limit are as follow:

- Load imbalance increased as the curve radius gets smaller. Two vertical dotted lines indicate 2500m and 600m radius curves. Trend increases exponentially in between these two limits.
- Limit of 1.25 is reached for a large range of curve radii (medium to small), but from these results the limit appears to be appropriate.
- Non-steady state conditions (x and +) don't appear to lead to an obvious increase imbalance.
- The locomotive (red square and circle) are showing much higher load imbalance than the freight wagon.

Observations for the dynamic limit are as follow:

- Limit value of 1.5 is exceeded in a significant number of cases (up to around 1.6~1.8), which does not coincide with the shaper curve radii.
- Both locomotive and freight wagon show exceedance values.
- Some non-steady states also show exceedance in the same order of magnitude as steady state.

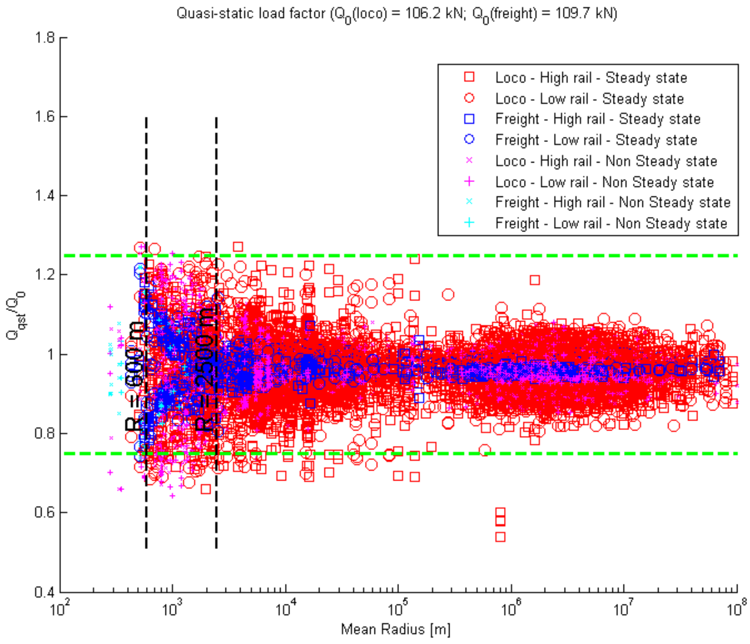

Figure 1: Quasi-static load factor (Qqst/Q_0) as a function of curve radius

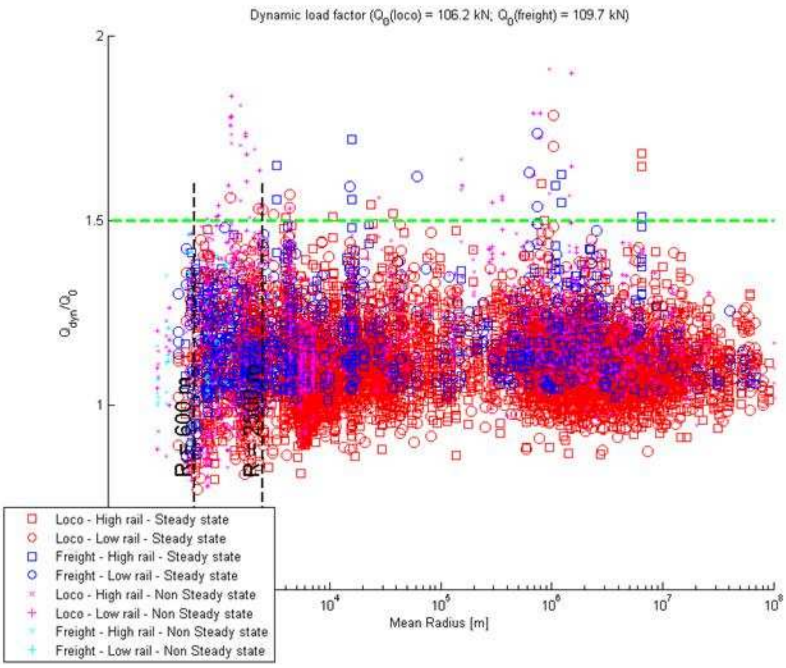

Figure 2: Dynamic load factor (Qdyn/Q_0) as a function of curve radius

3.2.2 Influence of vehicle speed and track category

Figure 3 shows quasi-static load ratio for the locomotive for different track categories and vehicle recorded speed. This shows that most of the high imbalances (+/-25%) occur when the vehicle reaches the speed limit for a specific speed category (<120km/h and 120 to 160km/h). In speed category 160 to 200km/h, the load imbalance remains within +/-10% because of favourable operating cant deficiency and less tight radius curves. No measurements are available above 200km.

Figure 4 shows the dynamic factor. Exceedances are also observed for speed category 120 to 160km/h while the vehicle speed is in the range 100 to 160km/h (one exception at very slow speed). Non steady state conditions lead to larger exceedance just below the 160km/h limit. On track category 160 to 200km/h, the track quality being higher, no exceedances are observed.

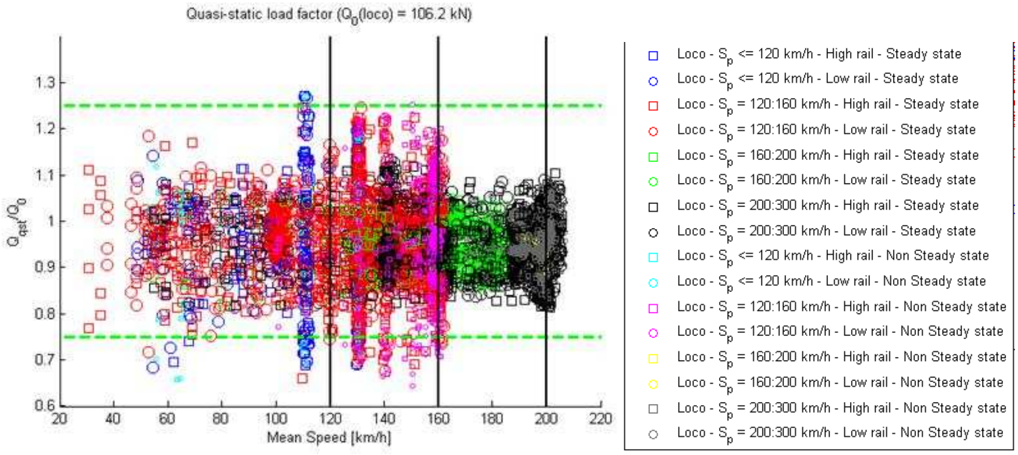

Figure 3: Quasi-static load factor (Qqst/Q_0) against vehicle speed

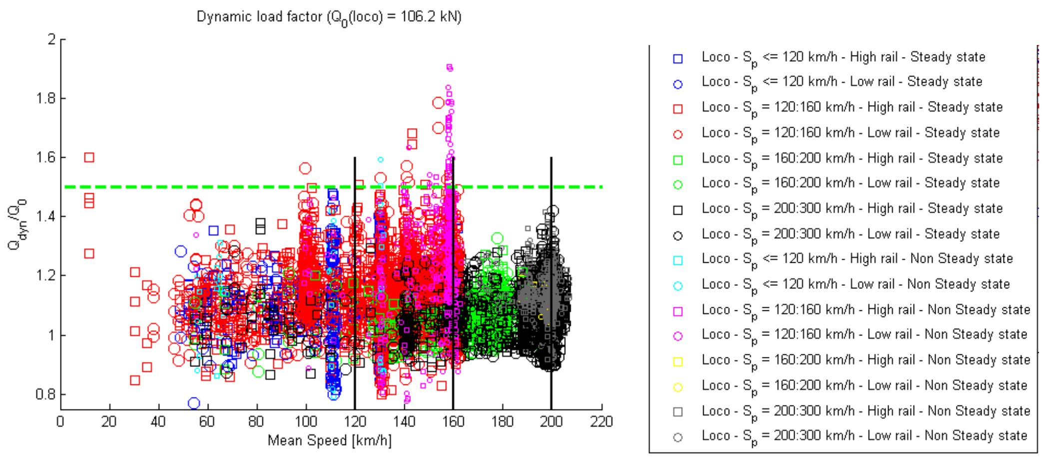

Figure 4: Dynamic load factor (Qdyn/Q_0) against vehicle speed

3.2.3 The influence of cant deficiency

In Figure 5 the load imbalance appear to represent a cross shape, with the extreme values reached for the extreme values of cant deficiency or cant excess. Dynamic load factor is not influenced by cant deficiency.

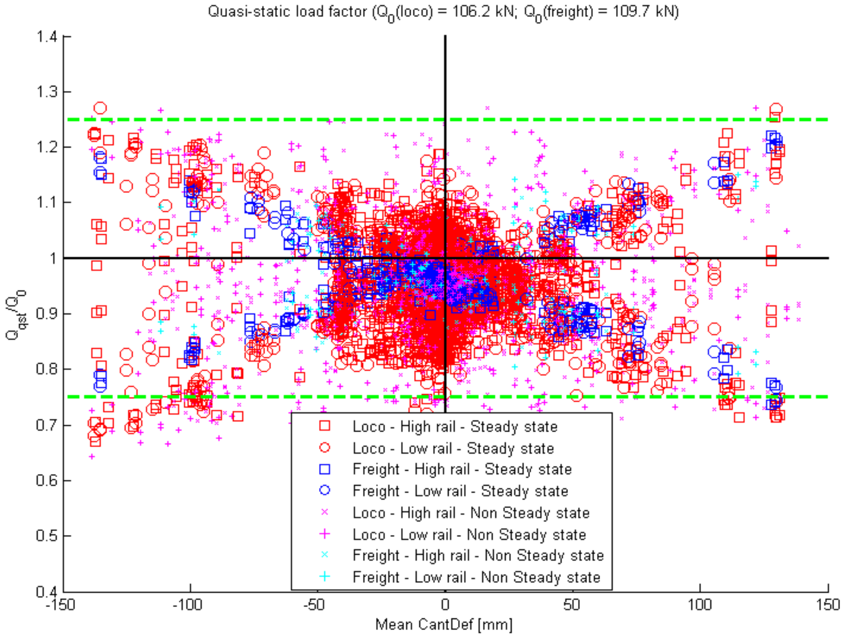

Figure 5: Quasi-static load factor (Qqst/Q0) against cant deficiency

3.2.4 Influence of track quality (horizontal level)

Figure 6 shows that the dynamic load factor increases linearly with decreasing track quality (SDz higher values). However there is a high number of sections exceeding the reference limit even for high track geometry quality. Also remarkable are high track forces associated with non-steady state conditions and large track defects.

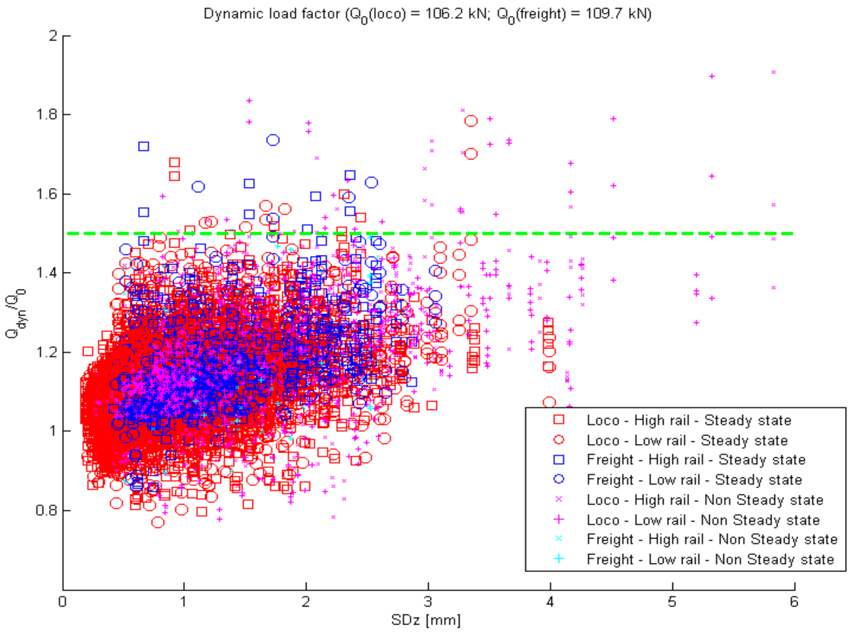

Figure 6: Dynamic load factor ($Qdyn/Q_0$) against track quality (vertical)

3.3 Lateral loads

3.3.1 Influence of curve radius on quasi-static forces

Quasi-static lateral forces Yqst are compared to the limit value of +/-60kN. It can be observed that the highest quasi-static lateral forces correspond to the smallest radii below around 2500m. Forces are otherwise much lower for very large radii and straight track as expected. The locomotive shows the large values also in large radius curves. A few isolated cases show values near or above the 60kN limit.

Lateral dynamics forces are not influenced by curve radius.

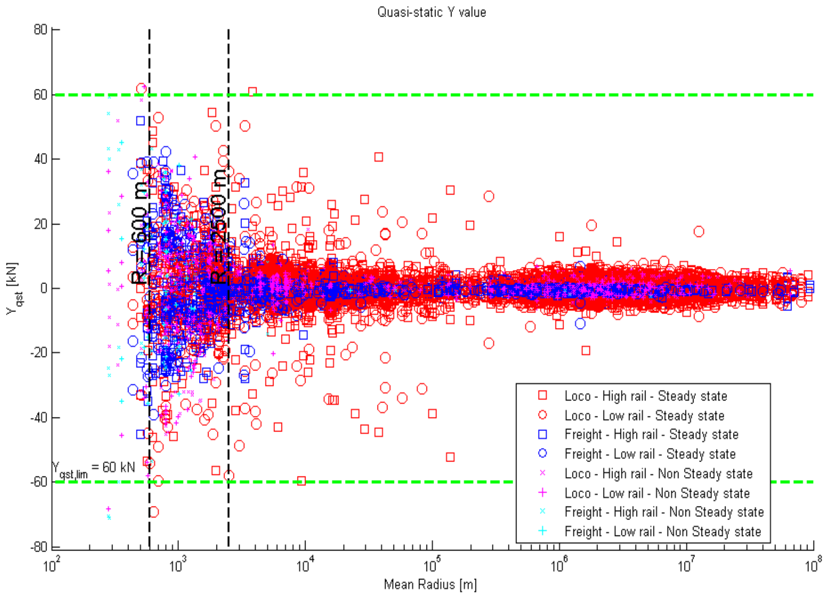

Figure 7: Quasi-static lateral forces Yqst as a function of curve radius

3.3.2 Influence of vehicle speed on dynamic forces

The dynamics lateral forces are more difficult to interpret because they are highly influenced by the wheel-rail conditions (equivalent conicity) and the vehicle reaction to track defects. Figure 8 shows than in each track category the lateral loads tend to increase as the vehicle speed increases. On low track categories (blue circle and square for <120km/h and red circle and square for 120 to 160km/h), high lateral response are seen also for slower speed, because of the tighter curving situation and the poorer track quality. Observed high values are in the order of +/-100kN as the limited quoted in [6].

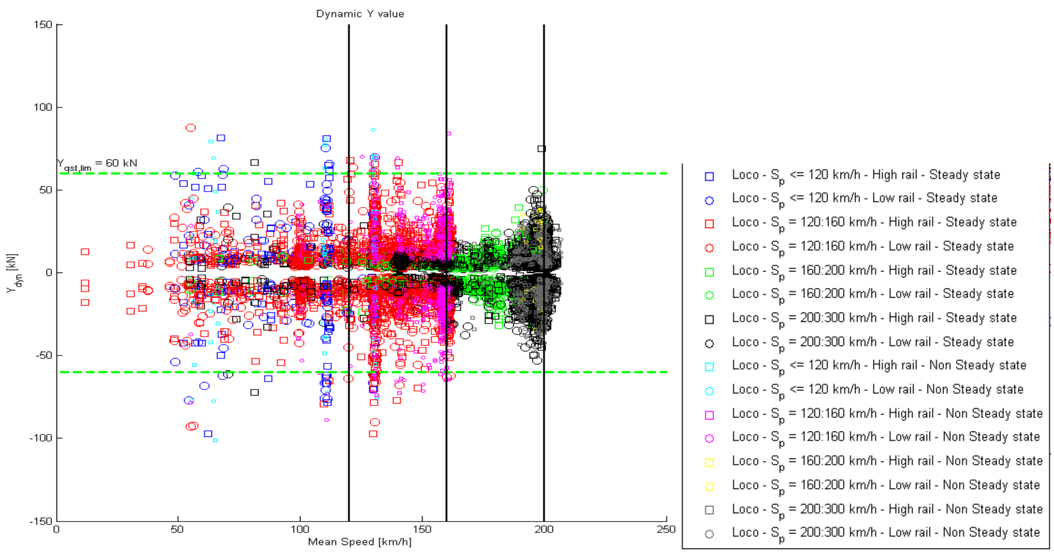

Figure 8: Dynamics lateral forces Ymax as a function of speed and track category

3.4 Track lateral shifting forces

According to [2], the safety-critical limit for track shifting forces based on Prud'Homme can be calculated as follow:

$$\Sigma Y_{2m\,max,lim} = k.(10 + \frac{2\,Q_0}{3}) \tag{2}$$

Where k factor depends on the vehicle type: 1.0 for locomotives, power cars, MU and passenger coaches; 0.85 for freight wagons. This equation is equivalent to equation (1) but for one axle rather than one wheel, therefore looking at the total lateral force leading to track shifting.

The dynamic track shifting force is shown in Figure 9 for leading axles of both locomotive and freight wagon. The following are observed:

- Values are generally comfortably below the limits with maximum in the order of +/-60kN
- There is a slight increase with tighter curve radius, however unlike Ymax there are also significant values in large radius curves and straight track.
- The locomotive here again shows the largest loads.

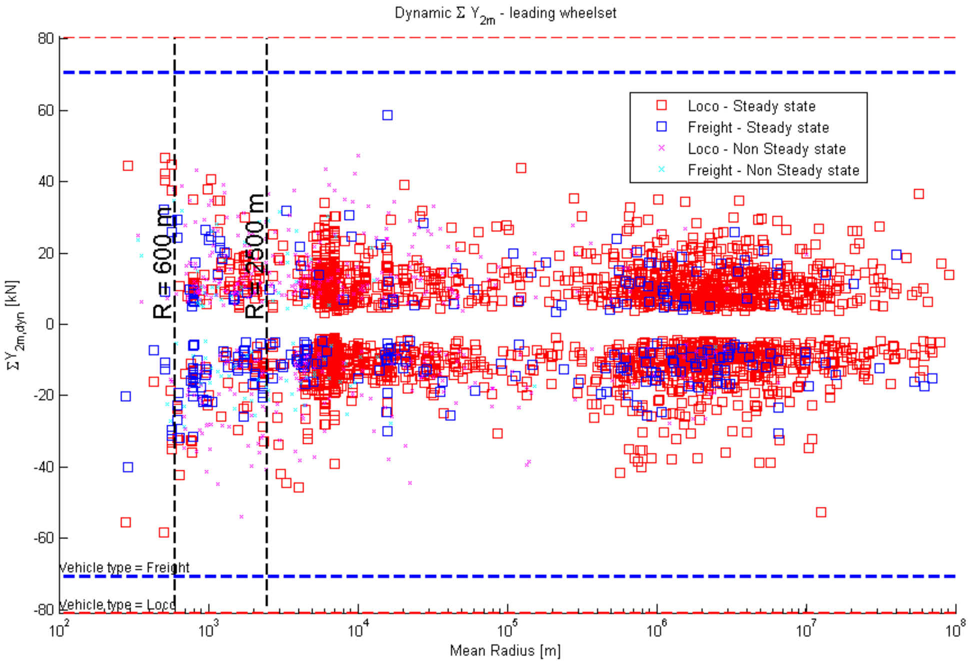

Figure 9: Track shifting force $\Sigma Y_{2m\,max}$ for leading axle of locomotive and freight wagon with respective limit values (dashed lines) against curve radius.

4 Additional load consideration and measurement observations

This section is investigating other track load combination known to be relevant from experience of vehicle dynamics analysis. In order to understand the relevance and magnitude of some of these additional load combinations, the same set of data as presented in section 3 is used with additional post-processing.

4.1 Proposed additional load combinations

The following loads will be investigated in this section, as illustrated in :

- Gauge spreading Ygs: difference between the right and the left wheel lateral force on each wheelset. This indicates issues with gauge retention and fastening damage.
- Bogie skewing Ybs (not presented here): difference between the sum of the lateral force on the first wheelset and the sum of the lateral force on the second wheelset; This indicate tendency for the bogie to skew the track as it moves along, with potential damage to fastening system and sleeper or slab residual movement.
- Bogie total Ybt: sum of the lateral force on each wheel of the bogie; This indicate the maximum chances for the full bogie to exert track shifting forces. If the combination is near or higher than single axle lateral force, it has more potential for track lateral residual movement.
- Rail twist Yrt: sum the lateral force on one rail in opposite direction between leading and trailing wheels. This means that during the bogie passage above the rail, the rail will be twisted (pushed into one direction, then the other). This can induced stresses within the rail that adds to residual and contact stresses to potentially help crack growth where RCF is present.

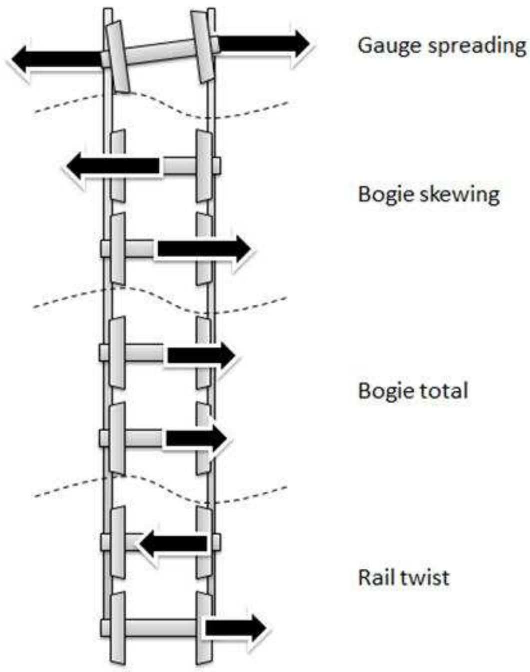

Figure 10: Additional load combination

4.1.1 Gauge spreading force

The gauge spreading forces are most important at the leading axle of a vehicle as this is the one experiencing the largest angle of attack in curves. Therefore the highest values are seen tightest curves with an exponential trend as seen in Figure 11. Maximum values are here in the order of 100kN with a few sections for the freight wagon at about 130kN. Dynamic values are not represented here but maxima are in the order of 150kN and are also large in straight and large curves (around 60kN).

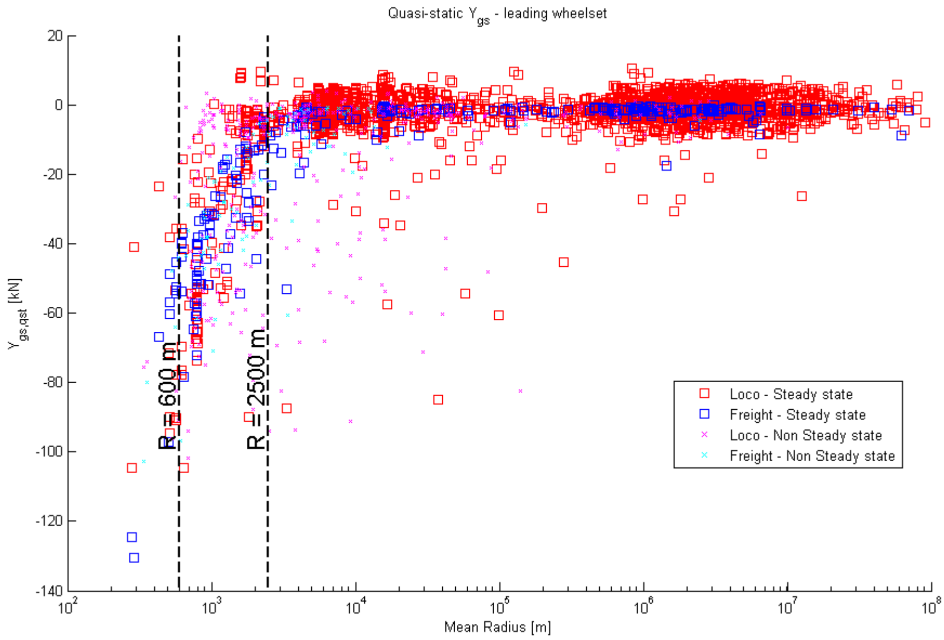

Figure 11: Quasi-static gauge spreading force on leading axle as a function of curve radius

4.1.2 Bogie total force

Bogie total lateral forces also increases in tighter curves together with increasing cant deficiency. Quasi-static values are in the order of +/-45kN (Figure 12) while dynamics values can be in the order of +/-80kN and also large in straight track. Although lower than the maximum lateral force observed on a single axle, it shows that it is important to take into consideration consecutive loads from the same bogie for track lateral resistance.

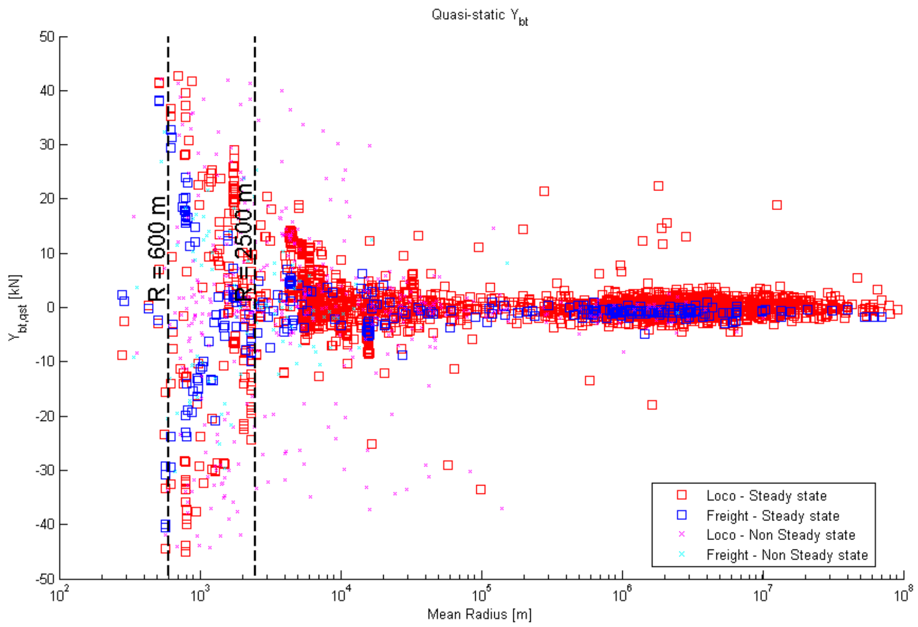

Figure 12: Bogie total lateral quasi-static force against curve radius

4.1.3 Rail twist torque

In Figure 13 the rail twist forces also increase with tightening radius curve up to value of around 70kN difference between one wheel and the next one. Dynamic values are in the order of 100kN. Here also this load combination might have an impact in rail defect evolution and fastening system have an important role to play in ensuring a good control of rail twist and roll.

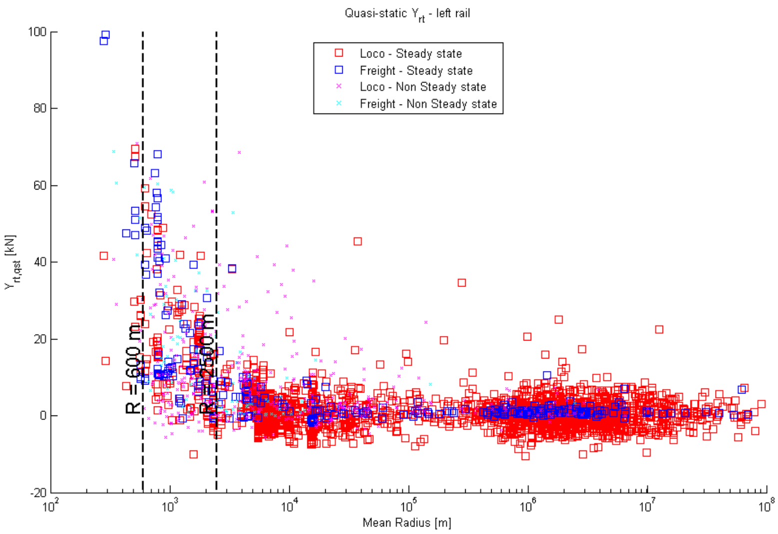

Figure 13: Quasi-static rail twist torque against curve radius

5 Conclusions and further works

In this paper the loading requirement for ballasted and ballastless track have been reviewed in the terms of existing reference loads and guidelines existing in EN standard and TSIs. The main source of information have been found to be derived either from vehicle testing (EN14363:2013) or bridge structure (EN1991-2:2003). Typical vehicle-track interaction loads have been described along with their influential factors and a categorisation against their frequency has been presented with reference limits where available.

The paper then describes the possible load limits based on the statistical analysis of a large measurement set of vehicle-track forces, while presenting relevant measures against their influential factors (e.g. curve radius or vehicle speed). Based on these observations the current limit values for Qqst, Yqst, Ymax and $\sum Ymax$ are found to be coherent and mostly applicable to heavy freight and locomotives. Maximum dynamics load in vertical direction are found to be sometime exceeding a factor of 1.5 on poor track geometry. Arguably the use of slab track construction should prevent track geometry degradation as observed on regional mixed traffic ballasted tracks, so that a more conservative approach might be taken in the design of slab track. Also where heavy freight and heavy locomotive are not foreseen, or where it can be shown that future vehicle will provide much better ride and steering

characteristics, some saving can also be expected from the track design point of view.
This paper also present additional load combination such as the gauge spreading forces, or rail twisting forces, which have been found to be non-negligible and potentially important in the generation of certain damage mechanisms.
Finally it can be concluded that measurement from vehicle testing can provide an important source of information in terms of expected track loading and their limit values, so as vehicle dynamics modelling, which should be used wherever possible to inform on track loading for the purpose of track design.

5.1 Further work

Areas of further work include:

- a wider statistical analysis using a more complete set of measurement data
- Characterisation of track loads based on vehicle dynamics simulations
- Assessment of further track load combination using analytical FEM methods on ballast and slab track systems

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